ELECTRON CLOUD EFFECTS IN KEKB

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Abstract

Measurements of the electron cloud effects in KEKB have been done since ECLOUD02 workshop. The results are summarized as 1) strength of the solenoid field in the present solenoid system is not enough to suppress the blow-up of the vertical beam size at high bunch currents and/or narrow bunch spacing, 2) solenoids in straight sections as well as arc sections contribute to suppress the electron cloud, 3) wiggler magnets have an effect on the blow-up of the vertical beam size but not on the tune shift and 4) regions where field orientation of adjacent solenoids changes have almost no effect on the blow-up and the tune shift and 5) a vertical tilt along a bunch, which might be an indication of the head-tail instability due to the electron cloud, is not clearly observed by the measurement by a streak camera.

INTRODUCTION

The KEK B-factory (KEKB) is an asymmetric energy electron-positron collider which is operated to study the physics of B mesons [1]. A blow-up of the vertical beam size has been observed in the KEKB low energy positron ring (LER) since the beginning of the operation [2]. A theory shows that the blow-up is caused by the head-tail instability due to the electron cloud (e-cloud) [3]. So far, the main measure against the blow-up is installation of weak solenoid magnets which sweep out the e-cloud [4,5]. Although most of drift regions are covered by the solenoids, the blow-up is still observed at high bunch currents and/or narrow bunch spacing. Thus the blow-up is still an issue of the luminosity upgrade. Important questions or concerns are where electrons are and how can the electrons be removed. Early experimental studies about the e-cloud were reported at ECLOUD02 workshop [6]. This paper reviews the measurements of the e-cloud effects in the KEKB which were done after ECLOUD02.

EFFECT OF SOLENOIDS

Since ECLOUD02 584 solenoids and 396 permanent magnets were installed in the LER. The permanent magnets cover beam position monitors (BPM's) and produce a longitudinal magnetic field of 45 Gauss in the center of a BPM chamber [7]. Presently, about 10000 solenoids and permanent magnets cover 78% of the circumference of the ring.

Effect of the solenoid field on the blow-up

As the energy of most photoelectrons which are the primary source of the e-cloud is less than several tens of eV, the maximum strength of the solenoid field was set to about 45 G which was expected to be enough to suppress the e-cloud. The measurement of a threshold current of the blow-up after first installation of the solenoids in 2000 showed that 20 G was enough to saturate the threshold current of the blow-up [4]. In the summer of 2002, 266 short solenoids were installed. Then the threshold current of the blow-up raised. A calculation showed that the length covered by the solenoid field larger than 60 G increased by 20% by the installation of the short solenoids. Though the effect of the short solenoids on the blow-up was not measured by switching off them selectively, if they were really effective, the measurement might suggest the stronger field is better to suppress the blow-up. Another consideration was the bunch current had increased by factor 3 since the first measurement of the solenoid effect. The increase of a bunch charge changes a kick to the e-cloud by the beam [8]. The field of 20 G may no longer be enough to saturate the threshold current of the blow-up. Thus we again measured the blow-up and the tune shift as a function of the solenoid field [9].

Figure 1 shows the measurement of the threshold bunch current as a function of the solenoid field at several bunch spacing. In case of 3 and 4 rf bucket spacing the threshold current is not saturated even at the maximum solenoid current. A calculation for the solenoids in one eighth of an arc section shows that the length covered by the solenoid field larger than 20 G saturates at 70% of the excitation and can not explain the saturation behavior of the threshold current of the blow-up. Thus not the fringe field but the central field will contribute to increase the threshold current. In 2 rf bucket spacing the threshold current saturated at 20 G and was not improved by stronger solenoid fields.

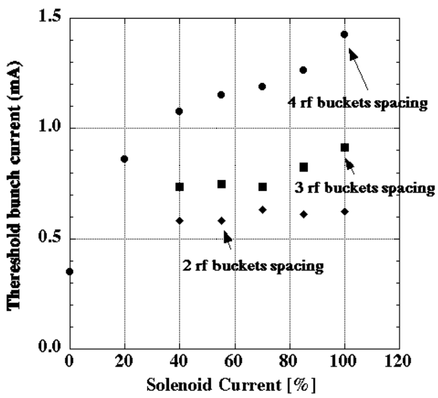

Figure 1: Threshold bunch current as a function of the solenoid current at the bunch spacing of 2, 3 and 4 rf buckets. The current of 100% corresponds to a solenoid field of 45 G.

Effect of the solenoids on the tune shift

According to a theory by K. Ohmi et al. [10], a horizontal or vertical tune shift $\Delta\nu_{H,V}$ by the e-cloud is written as

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$$\Delta\nu_{H,V} = \frac{r_e}{2\gamma} \cdot \oint \rho \cdot \beta_{H,V} \cdot ds, \qquad (1)$$

where ρ is the e-cloud density, $\beta_{H,V}$ the beta function, γ the Lorentz factor, r_e the classical radius of the electron and s the orbit length. The tune of each bunch increases along the train and saturates due to the build-up of the e-cloud. The tune shift can be a better measure of an amount of the e-cloud than the threshold current of the blow-up because the tune shift does not depend on the mechanism of the instability.

Fig. 2 shows the saturated tune shift measured by a gated tune meter [11] as a function of the bunch current I_b with and without the solenoid field [12]. Without the solenoid field $\Delta\nu_{H,V}$ increase linearly with the bunch current. The vertical tune shift at the threshold of the blow-up was 0.01 which is consistent with a predicted tune shift of 0.008 at the threshold of the instability by a simple head-tail model [3,10]. $\Delta\nu_H$ and $\Delta\nu_V$ have different slopes $d\Delta\nu/dI_b$. With the solenoid field on, $\Delta\nu_H$ is almost zero, while $\Delta\nu_V$ still increases with the bunch current. Asymmetry of the horizontal and vertical tune shift and a large $\Delta\nu_V$ may be a hint to understand why the blow-up still remains after installation of the solenoids.

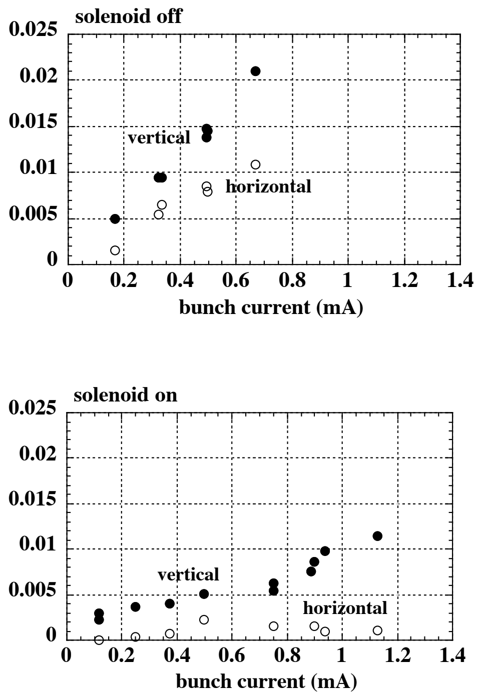


Figure 2: Horizontal and vertical tune shift as a function of the bunch current when the solenoids are switched off and on.

Fig. 3 shows the tune shift along a bunch train in several solenoid fields at the bunch current of 0.5 mA. The field of 50% of the maximum excitation is enough to saturate the tune shift.

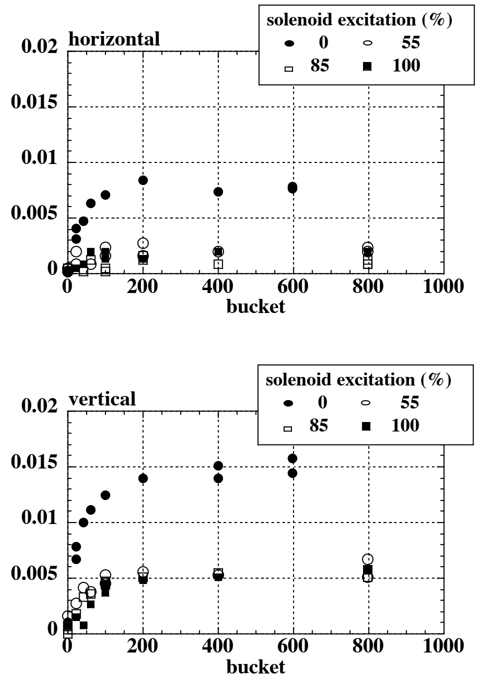


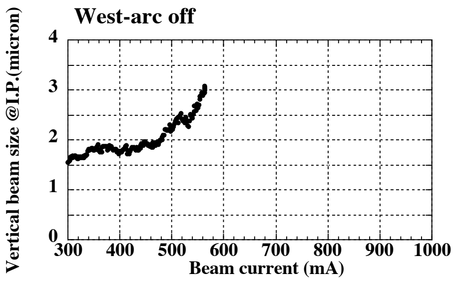
Figure 3: Horizontal and vertical tune shift along the bunch train in several solenoid fields. The bunch spacing is 4 rf buckets and the bunch current is 0.58mA.

Effect of the solenoid locations on the blow-up and the tune shift

KEKB consists of four arc sections and four long straight sections. Two straight sections, named Oho and Nikko straight sections have long wiggler sections as described in the next subsection. Since the LER has no ante-chamber, the main source of the e-cloud is expected to be the photoelectrons produced by synchrotron radiation in the arc and wiggler sections. Nevertheless the e-cloud may form in the other two straight sections, Fuji and Tsukuba straight sections, by beam-induced multipacting. To see a contribution of the solenoids in various locations to the e-cloud, the blow-up and the tune shift were measured by switching off the solenoids locally [9,12].

Fig. 4 shows the vertical beam size measured by a synchrotron light interferometer [13] when switching off the solenoids in the arc and the Fuji straight section. The beam size at the emission point of the synchrotron radiation is converted to that at the collision point.

The result shows that the solenoids in the Fuji straight section where no wiggler magnets are installed contribute for mitigating the blow-up.



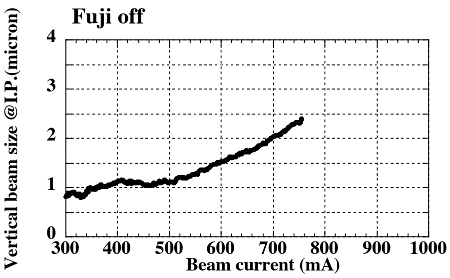


Figure 4: Vertical beam size measured by the interferometer when switching off the solenoids locally. The number of the trains is four, the number of the bunches in a train is 200 and the bunch spacing is 3 rf buckets. Top : West arc section off; bottom : Fuji straight section off.

Table 1-a) shows the change of the tune shift when switching off the solenoids in various locations. Table 1-b) shows the average electron density $\rho_{\text{ave.}}$ suppressed by the turned-off solenoids which is estimated from the tune shift in Table 1-a) and the beta function as

$$\rho_{\text{ave.}} = 2\gamma / r_e \cdot \Delta\nu_{H,V} / \int_{\text{drift region}} \beta_{H,V} \cdot ds \qquad (2)$$

where $\Delta\nu_{H,V}$ is the saturated tune shift when switching off the solenoids. In Table 1-b) the estimated electron density in vertical plane in the straight sections is large. This result may indicate the asymmetric tune shift comes from the straight sections.

Effect of a gap between adjacent solenoids on the blow-up and the tune shift

The field orientation of the solenoids between adjacent quadrupoles is arranged such that the field of half of the solenoids points the upstream direction of the beam and that of the remaining solenoids does the downstream direction in order to vanish the integrated solenoid field to avoid X-Y coupling effect. Thus there is a region between the adjacent quadrupoles where the field direction changes. The total number of this region is about 460 in the ring. A question that the electrons might be accumulated in these regions has been raised. To check such a possibility, a polarity of the solenoids in three arc sections, i.e. 258 regions, was changed such that the field of all solenoids between adjacent quadrupoles pointed in the same direction. The measurement before and after changing the configurations of the polarity shows that almost no change was observed in the blow-up and the tune shift. A simulation by L. Wang et al. [8] shows the electron line densities in two configurations are close each other. Comparing the radial distribution of the electrons in two configurations more electrons stay near a chamber wall under latter configuration, but the electron densities at the center of the chamber is almost same and close to zero which supports the experimental result that almost no change was observed in the blow-up in two configurations because the blow-up is expected to be caused by the interaction between the beam and the electrons at the beam position.

Table 1-a): Change of the tune shift when the solenoids are switched off.

	Horizontal	Vertical
All arc sections off	0.006	0.006
All straight sections off	0.0035	0.008
Tsukuba straight section off	0.001	0.003
All solenoids off	0.0085	0.015

Table 1-b): Estimated average electron density which is suppressed by the solenoids in the region written in the leftmost column. Unit is 10^{12} m^{-3}.

	Horizontal	Vertical
All arc sections	1.17	1.17
All straight sections	1.17	1.90
Tsukuba straight section	1.20	1.31
Whole ring	1.10	1.60

EFFECT OF WIGGLER MAGNET

In order to study the effect of the e-cloud inside bending magnets, the blow-up and the tune shift were measured by switching on and off wiggler magnets. The total length of the wiggler magnets is about 100 m which is about same as total length of lattice bending magnets. The field strength of the wiggler magnets is 0.75 T which is also same as the strength of the lattice bends. When the wiggler magnets are turned off the natural emittance increases from 19 to 30 nm and the transverse radiation damping time does from 43 to 87 ms. The bunch length does not change.

Fig. 5 compares the tune shift along the train with switching on and off the wiggler magnets. No large difference was observed in the tune shift. Fig. 6 shows the vertical beam size with switching on and off the wiggler magnets. A large difference was observed in the beam size. Application of a weak magnetic field of 40 G did not affect to the tune shift and the blow-up. The large effect of the wiggler magnets on the blow-up may be due to the change of the radiation damping time which works on the stability of the beam and no effect on the tune shift may indicate an amount of the e-cloud is almost same with and without the wiggler magnets. Further studies are necessary to answer to these speculations.

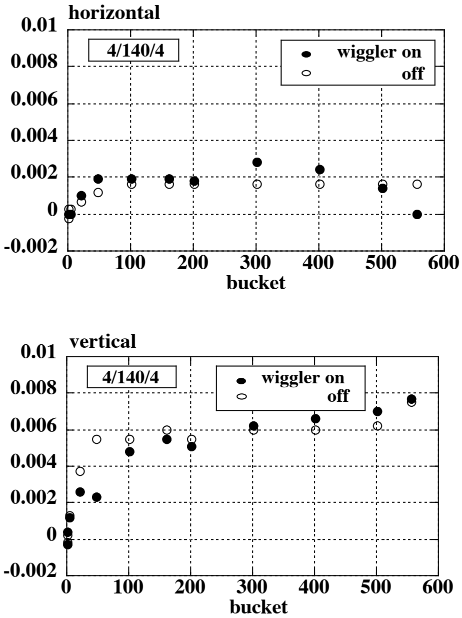


Figure 5: Horizontal and vertical tune shift along the bunch train with the wigglers on and off. The number of the train is four, the number of the bunches in a train is 140 and the bunch spacing is 4 rf buckets.

MEASUREMENT OF HEAD-TAIL MOTION BY THE E-CLOUD BY A STREAK CAMERA

According to the theory by K. Ohmi and F. Zimmermann the blow-up of the beam size is caused by the head-tail instability due to the e-cloud [3]. In order to detect the head-tail motion a bunch profile was measured by a streak camera [9].

A resolution of the streak camera $\sigma_{\text{resolution}}$ was measured by the following procedures [14]:

1. Change the beam size by an orbit bump at a sextupole.
2. Measure the beam size by the streak camera and the interferometer at the same time.
3. Fit the data to

$$\sigma_{\text{streak}} = a \cdot \sqrt{\sigma^2_{\text{resolution}} + \sigma^2_{\text{interferometer}}}\,, \qquad (3)$$

where σ_{streak} and $\sigma_{\text{interferometer}}$ are the beam sizes measured by the streak camera and the interferometer respectively and a is a constant.

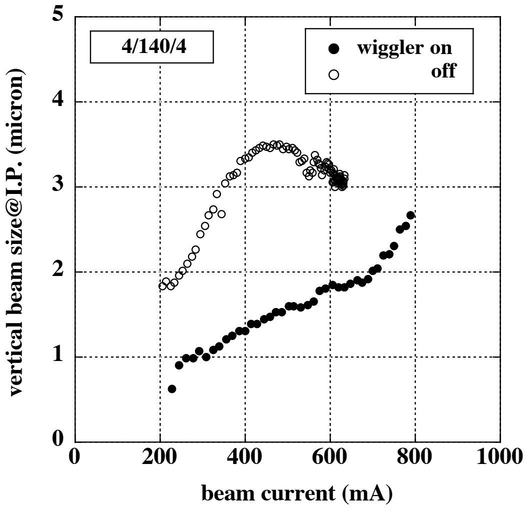


Figure 6: Vertical beam size as a function of the beam current with the wigglers on and off. The number of the train is four, the number of the bunches in a train is 140 and the bunch spacing is 4 rf buckets.

The result shows that $\sigma_{\text{resolution}}$ is 199 μm which is consistent with an estimated spread of a point image by diffraction, namely 190 μm. The resolution of 199 μm is equivalent to 3.8 μm at the collision point.

Fig. 7 shows a preliminary result. The vertical beam size starts to increase at the third or fourth bunch when the solenoids are switched off, while such an increase is not seen with the solenoids on. A vertical tilt within a bunch is not clearly observed even in the tail part of the train where a large cloud density is expected. An increase of the light intensity and/or sophisticated analyses is necessary to get a clearer result.

SUMMARY

Observations of the e-cloud effects in the KEKB LER after ECLOUD02 are summarized as follows.

1. The threshold current of the blow-up is improved through increasing the solenoid field if the bunch spacing is larger than or equal to 3 rf bucket spacing.
2. The e-cloud is generated both in the arc and the straight sections according to the measurement of the blow-up and the tune shift.
3. The zero crossing regions of the solenoid field between the adjacent solenoids have no effect on the blow-up and the tune shift.
4. The wiggler magnets affect to the tune shift and do not to the blow-up.
5. A clear vertical tilt within a bunch is not observed by the measurement by the streak camera.

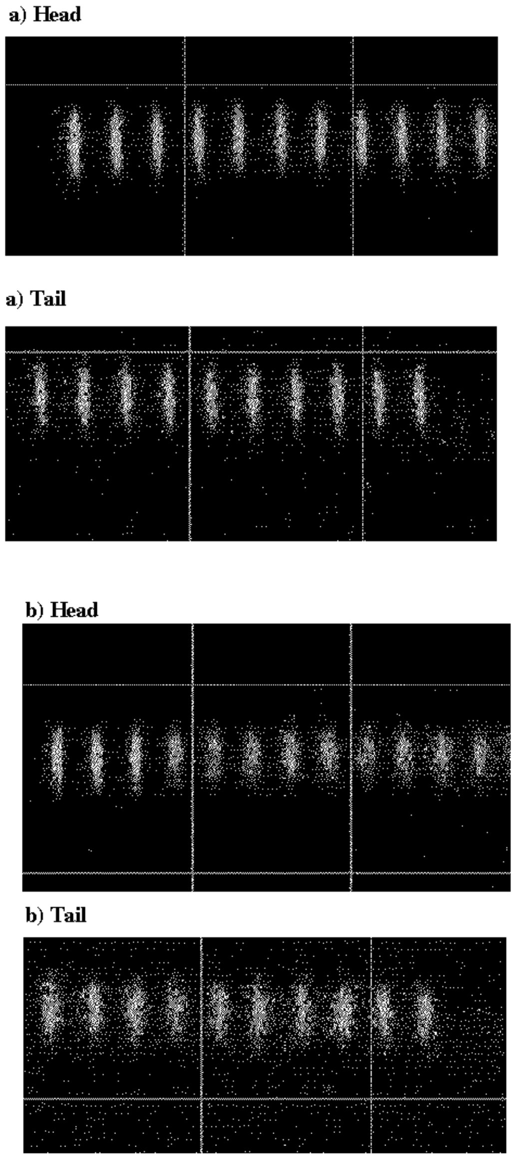


Figure 7: Bunch shape in the head and tail part of the train taken by a streak camera (preliminary). a) Solenoid on, bunch current 1mA; b) Solenoid off, bunch current 0.9mA. Bunch spacing is 4 rf buckets. The vertical direction of the pictures is along the bunch and the horizontal width of the bunch shape corresponds to the vertical beam size.

Some questions still remain to be solved:

1. What is the origin of the asymmetric horizontal and vertical tune shift?
2. Why the vertical tune shift is still observed after installing many solenoids in the drift regions?
3. How can we understand the effect of the wiggler magnets?
4. The vertical beam size as a function of the beam current slowly increases below the threshold current of the blow-up. What causes this slow blow-up?
5. The measurement by the streak camera shows the enlargement of the beam width, while no clear tilt within a bunch is observed. Is there any mechanism which causes the enlargement of the beam width by the e-cloud?
6. What is the behavior of the e-cloud in a strong magnetic field such as quadrupole and bending magnets?

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